A Fast Contingency Screening Algorithm for On-line Transient Security Assessment Based on Stability Index

Hae-Kon Nam*, Yong-Hak Kim, Sung-Geun Song*** and Yong-Gu Kim***

Abstract - This paper describes a new ultra-fast contingency screening algorithm for on-line TSA without time simulation. All machines are represented in a classical model and the stability index is defined as the ratio between acceleration power during a fault and deceleration power after clearing the fault. Critical clustering of machines is done based on the stability index, and the power-angle curve of the critical machines is drawn assuming that the angles of the critical machines increase uniformly, while those of the non-critical ones remain constant. Finally, the critical clearing time (CCT) is computed using the power-angle curve. The proposed algorithm is tested on the KEPCO system comprised of 900-bus and 230-machines. The CCT values computed with the screening algorithm are in good agreement with those computed using the detailed model and the SIME method. The computation time for screening about 270 contingencies is 17 seconds with 1.2 GHz PC.

Keywords: transient stability, contingency screening, equal area criterion, power-angle curve, critical clearing time.

1. Introduction

The uncertainty of transaction scheduling and the increased exposure to system failures from operating power systems in highly stressed conditions makes it critical to quickly and accurately determine the dynamic security of power systems, especially for real time operation. Transient security assessment (TSA) is important in power system planning and operation.

Time-domain methods (TDM) have been used for transient stability studies. They can compute stability limits (critical clearing time or power transfer limits). However, they would require prohibitive computing time to handle many contingencies. Each simulation will classify contingencies into "stable" and "unstable" with respect to a given clearing time without much information on margin. Time simulation has the advantage of being able to accommodate sophisticated models.

The direct methods have complementary possibilities [1]. They enable sensitivity analysis, which is very difficult with time simulation, and can be faster in principle. For contingency screening and ranking in the transient stability, various methods have been developed [2-6].

The hybrid method combines the direct method and time simulation. Recently, sophisticated hybrid methods based on EEAC [7-10] have been developed, and have been recognized to be reliable and useful in terms of modeling flexibility and computational efficiency. Since the methods need several time simulations for screening and ranking each given contingency, computing time for contingency screening and ranking (CS&R) of large systems may not be trivial. Computational efficiency can be significant if CS&R can be performed without time simulation.

This paper describes a new ultra-fast contingency screening algorithm for first swing transient stability studies without time simulations. The proposed method is developed based on the Extended Equal-Area Criterion (EEAC) with simplifying assumptions. All machines are represented in a classical model and the stability index is defined as the ratio between acceleration power during a fault and deceleration power after clearing the fault. Critical clustering of machines is done based on the stability index, and power-angle curves of the critical machines are drawn assuming that the rotor angles of the critical machines increase uniformly, while those of the non-critical ones remain constant. Finally, critical clearing time (CCT) is estimated using the power-angle curves. The proposed algorithm is tested on the KEPCO system comprised of 900-bus and 230-machines. The CCT values computed with the proposed screening algorithm are in good agreement with those computed using the detailed model and the Single Machine Equivalent (SIME) method. The computation time for screening about 270 contingencies is 17 seconds with 1.2 GHz PC.

---

* Department of Electrical Engineering Chonnam National University, Gwangju, 500-757, Korea.

** Power System Analysis GroupKorea Electric Power Research Institute, 103-16 Munji-dong, Yusung-ku, Daejon, 305-380, Korea.

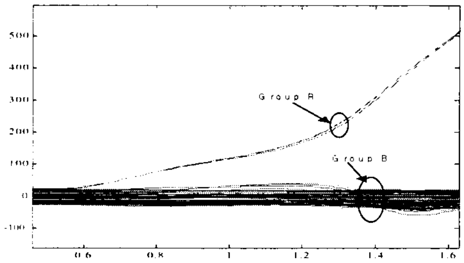
*** Procom, 1-19 Chungdam-dong, Kangnam-ku, Seoul, 135-100, Korea

Received October 15, 2002 ; Accepted December 3, 2002

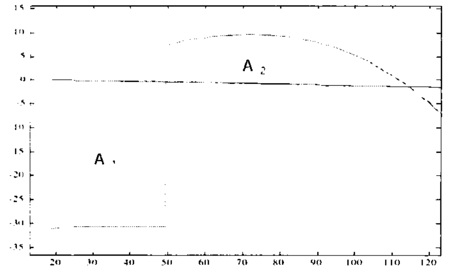
2. Sime Method

The proposed method in this paper imitates the SIME method without time simulation. Also the CCT values calculated by the SIME method are used as the reference in checking the accuracy of the screening results. For clarity of description, the SIME method is briefly summarized here. Details are found in [1,8-9].

1. For a given contingency, the time domain simulation is performed with somewhat large clearing time until a group of generators reach an unstable condition; draw the swing curves of the system machines as in Fig. 1.a; in post fault configurations, continue until any two of the machines reach an angular deviation of 360°. Let t_{obs} be the corresponding observation time.
2. At t_{obs} sort the system machines in decreasing order of their rotor angles, and identify the largest angular deviations (maximum gap) between any two adjacent machines. All machines above the maximum gap are considered to be the critical machines.
3. Aggregate the critical machines into one equivalent machine; similarly, aggregate the remaining machines into another equivalent machine. Finally two equivalent machines are replaced by an one machine infinite bus (OMIB) system
4. At each time step, The OMIB parameters such as angle (δ), speed (ω), electrical power (P_e), and mechanical power (P_m) and power-angle curve (Fig. 1.b) are computed. The stability margin of the OMIB is computed using the equal area criterion.



(a) Time simulation



(b) Power-angle curve

Fig. 1 SIME method

3. Contingency Screening

CS&R with the SIME method needs a few iterations of time simulations for each contingency and CPU time may be prohibitively large if the number of contingencies is large. In case that limited number of critical contingency list is given by priori studies, CS&R by the SIME method is well suited. Otherwise, faster screening methods without using time simulation are desired. An ultra-fast contingency screening is possible by imitating the SIME method without time simulation.

3.1 Critical Clustering

Fig. 2 shows the Equal Area Criterion (EAC) of an OMIB system. The system is initially in operation at the point A. If a fault occurs, the transmitted electrical power is reduced significantly, while the mechanical power essentially remains constant. The generator starts acceleration. While the fault is on the system, the generator rotor angle increases along the curve BC. The initial acceleration power AB measures the severity of the fault. At point C, the fault is cleared and the synchronizing power increases to point E. The generator starts deceleration. Since the rotor speed deviation at this moment is positive, the rotor angle continues to increase until the deceleration area represented by part of DEF equals to the acceleration area ABCD. The equal area criterion states that the system is stable only if the acceleration area ABCD is less than or equal to the deceleration area DEF. Although the EAC is derived for the OMIB system, it can be applied to each generator of the multi-machine system with modification on the power-angle curve, which is influenced by the interactions among the machines in multi-machine systems.

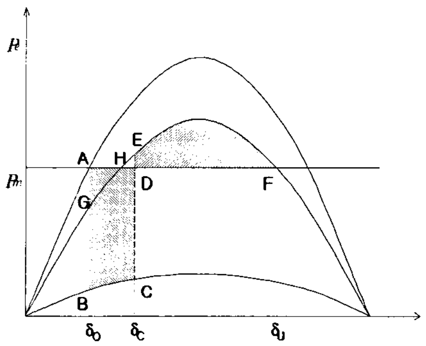


Fig. 2 The Equal Area Criterion

The EAC suggests about the first swing transient stability of the system that a generator becomes unstable when the acceleration power AB is large compared to the synchronizing power, which can be measured by the slope of the curve GHE at point E. Based on this observation, a stability index for critical clustering is defined as:

$$S_{index} = \frac{AB}{Syn} \tag{1}$$

The term in the right-hand side of equation (1) represents the ratio between the acceleration power and synchronizing power coefficient Syn is defined as

$$Syn = \frac{\Delta P_e}{\Delta \delta} \tag{2}$$

The procedure to determine the stability index in (1) is as follows:

1. Solve the network equation in the fault condition and determine the electrical power output of each generator. Identify the critical generators of which acceleration power is above the predetermined value, for example, 60% of the mechanical power P_m.
2. Increase uniformly the rotor angles of the critical generators by 30 degrees. Solve network equations, and compute Syn in (2) and S_{index} in (1) of each critical generator.
3. Sort the critical generators in decreasing order of their stability index, and identify the maximum gap in the stability index.
4. Re-identify the critical generators stability index of which is above the maximum gap. If the list of the critical generators is in agreement with the previous one, determine the CCT of the critical generators as described in the next subsection. Otherwise, reset the rotor angles of the generators to the values before the fault occurs, and go to step 2 with a new critical generator list.

In step 1, if the generators of which the acceleration power for the postulated contingency is less than the predetermined value, for example, 60% of the mechanical power, the contingency may not be critical with respect to the generator since each generator in the well-designed power system will, generally speaking, have adequate synchronizing power against the most severe contingency. Hence, the CCT of the generator will be much larger than the clearing time of the circuit breakers and there will not be a significant transient stability problem. The value of 60% of the mechanical power is determined by experience for the KEPCO system.

3.2 Computation of Critical Clearing Time

Once the critical generators are determined, the CCT is computed as a stability margin. If all generators and loads are modeled as voltage sources behind effective reactance (classical model) and constant impedances, respectively, it is known that the electrical power of each generator or the equivalent reduced OMIB system is given as a sine function of rotor angles [1]:

$$P_e(\delta) = P_0 + P_{\max}\sin(\delta - v) = P_0 + K_1 \sin\delta + K_2 \cos\delta \tag{3}$$

If generators are not represented as classical models or loads are not modeled as constant, the electrical power of each generator or the equivalent reduced OMIB system is given as a function of rotor angles close to a sine wave and can be approximated by a sine function in (3).

Contingency screening, in this paper, is done by estimating the CCT of each critical machine as:

1. In addition to two power-angle relationships obtained in section 3.A to determine the synchronizing power coefficients, compute two more power-angle relationships of the critical machines by increasing uniformly the rotor angles of the critical machines by 30 degrees twice, and solving network equations. At this stage, a total of four power-angle relationships with fault cleared are available.
2. Determine the coefficient P_0, K_1 and K_2 for each critical machine using the least square error estimation.
3. Compute the CCT for each critical machine using Newton's method so that the acceleration and deceleration areas are the same as the assumption that mechanical powers of the critical generators remain constant. The CCT of the system is taken as the minimum among the CCT values for all critical generators.

A total of four data sets of power-angle relations with a 30° angle interval are used for estimating the P-δ curve in (3). Hence, the rotor angle of the OMIB at the last data will be larger than that of the base point by 90°. This range of the rotor angles is enough for representing the P-δ curve of interest in transient stability studies.

4. Case Studies

The proposed contingency screening algorithm is tested on the KEPCO system with the long-term operational planning data for peak and off-peak load demands in the year of 2003. The KEPCO system in the year of 2003 comprises about 900-buses, 230-machines and an installed generation capacity of around 55,000 MW. The standard unit size is 1,000 MW for nuclear plants, and 500 MW for coal-fired steam plants. The transmission system consists of two 765 kV lines and highly meshed 345 kV lines with underlying 154 kV lines. Construction of two 765 kV routes is complete. One route is now in operation at 765 kV on the West Coast and the other on the East is at 345 kV. Each route of the transmission towers consists of two circuits of 345 kV and above.

Contingencies are 3-phase faults at each of all 345 kV and above lines and opening the faulted circuit. The CCT for each contingency is computed using both the proposed method and the SIME method. The SIME method is implemented using the IPLAN of PSS/E.

Table 1 summarizes the contingency screening results of the KEPCO system for off-peak loading condition in the year of 2003. Only the contingencies with small CCT values are shown for brevity. In the table, 'SIME' and "CS&S" represent the CCT value computed using the SIME method and the proposed contingency screening algorithm, respectively. "From" ("to") means that the 3-phase line fault occurs at the "from" ("to") bus.

The CCT values computed using the SIME and the proposed contingency screening algorithm are consistent and in good agreement. The maximum deviation is 3.5 cycles for line contingency 6151-6800. This accuracy is sufficient for use in contingency screening.

Table 2 summarizes the contingency screening results for the peak loading condition in the year of 2003. The CCT values computed using the SIME and the proposed contingency screening algorithm are consistent and in good agreement. The maximum deviation is 4 cycles for line contingency 7100-7151. The accuracy for this may be sufficient for use in contingency screening, too.

The computation time for the critical clustering and screening of about 270 contingencies is 17 seconds with 1.2 GHz PC.

Table 1 Contingency Screening Results for Off-Peak Loading Condition in the year of 2003

Line Contingency		CCT [cycle]			
Bus No		SIME		CS&S	
From	To	From	To	From	To
1500	5150		7.5		8.7
4010	6030	13.5	10.5	13.0	11.3
5150	5500	7.1	13.4	8.5	14.5
5150	5600	7.3	11.7	8.6	13.1
6100	6900	10.1	11.1	13.3	14.6
6101	6300	10.1	10.2	13.2	12.6
6150	6950	10.5	11.5	12.4	14.4
6151	6800	10.5		11.8	17.0
6300	6900	10.4	11.3	12.9	14.8
6300	6950	10.1	11.5	12.6	14.9
6450	7150	14.2	10.1	15.6	11.0
6450	7151	4.6	2.6	5.9	3.4
7100	7150	12.1	10.1	14.1	11.3
7100	7151	6.4	4.5	10.4	6.2
10150	10700	9.8	13.1	12.5	15.0
10150	10800	9.9	14.4	12.6	16.1

Table 2 Contingency Screening Results for Peak Loading Condition in the year of 2003

Line Contingency		CCT [cycle]			
Bus No		SIME		CS&S	
From	To	From	To	From	To
1500	5150		7.0		7.0
4010	6030	11.0	9.5	12.2	10.8
4400	6950	11.3	8.0	12.9	8.7
5150	5500	6.9	12.9	6.9	10.7
5150	5600	7.3	11.4	7.2	10.6
6100	6900	8.2	8.3	12.3	11.5
6101	6300	8.2	8.5	12.3	11.0
6150	6950	9.5	8.2	11.3	9.6
6151	6800	7.4	11.0	10.7	14.5
6300	6900	8.3	9.1	11.4	11.9
6300	6950	8.5	8.3	10.9	8.7
6450	7150	14.4	9.9	14.4	9.8
6450	7151	4.8	2.3	3.5	3.5
7100	7150	11.3	9.7	10.5	10.2
7100	7151	5.4	3.5	6.8	4.6
10150	10700	9.5	12.9	12.1	14.3
10150	10800	9.6		12.2	15.0

5. Conclusions

The ultra-fast contingency screening algorithm for the transient security assessment is proposed in this paper. This method can evaluate the first-swing stability of a large number of contingencies in a short time with reliable accuracy. Faster contingency screening was possible with the improved screening algorithm as:

1. Identify the critical cluster of generators by a new stability index. The stability index, which is defined as the ratio of the acceleration power of generators at the moment of fault and synchronizing power coefficient after clearing the fault, is obtained simply by solving network equations, not by time simulation.
2. Compute the power-angle trajectory of the critical generators at four points with an interval of 30^0. For this purpose, the angles of the critical generators uniformly increase by 30^0, while the angles of the rest of the machines remain constant.
3. The power-angle data of each critical machine is fitted as a sine function with least square error estimation, and the CCT values are computed using Newton's method.

The test results on the KEPCO system show that the proposed method can be used as a contingency screening tool for the first-swing transient stability studies. The computation time for the critical clustering and screening of about 270 contingencies is 17 seconds with 1.2 GHz PC.

Acknowledgements

The work is supported in parts by KEPCO under its grants including 00-Joong-04.

References

[1] M. Pavella, P. G. Murthy, "Transient Stability of Power Systems: Theory and Practice", John Wiley & Sons, 1994.

[2] C. Fu, A. Bose, "Contingency Ranking Based on Severity Indices in Dynamic Security Analysis", IEEE Transaction on Power Systems, Vol. 14, No. 3, August 1999, pp. 980-986.

[3] A.A. Fouad, V. Vittal, "The Transient Energy Function Method". Electrical Power and Energy Systems, Vol. 10, No. 4, October 1988, pp.233-246.

[4] Y. Xue, T. Van Cutsem, M. Pavella, "Extended Equal Area Criterion. Justifications, Generalizations, Applications", IEEE Transactions on Power Systems, Vol.4, No.1, pp.44-52, February 1989.

[5] V. Chadalavada, V. Vittal, G.. C.. Ejebe, G. Irisarri, J. Tong, G.. Pieper, M. McMullen, "An On-Line Contingency Filtering Scheme for Dynamic Security Assessment", IEEE Transactions on Power Systems, Volume 12, No. 1, February 1997, pp. 153-162.

[6] Y. Mansour, E. Vaahedi, A.Y. Chang, B.R. Coms, B. Garrett, K. Demarce, T. Athay, K. Cheung, "B.C. Hydro's On-line Transient Stability Assessment (TSA) Model Development, Analysis and Post Processing", IEEE Transactions on Power Systems, Volume 10, No. 1, February 1995, pp. 241-253.

[7] Y. Zhang, L. Wehnkel, P. Rousseaux, M. Pavella, "SIME: A Hybrid Approach to Fast Transient Stability Assessment and Contingency Selection", Electric Power & Energy Systems, Vol.19, No.3, 1997, pp.195-208.

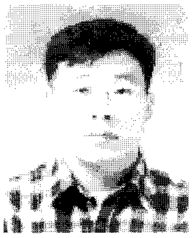
[8] Y. Zhang, L. Wehnkel, M. Pavella, "SIME: A Comprehensive Approach to Fast Transient Stability Assessment", Trans. of IEE Japan, Vol.118-B, No.2, 1998, pp.127-132.

[9] D. Ernst, D. Ruitz-Vega, M. Pavella, P. Hirsch , D. Sobajic 0, "A Unified Approach to Transient Stability Contingency Filtering, Ranking and Assessment", IEEE Transactions on Power Systems, Vol. 16, No.3, pp.435-433, August 2001.

[10] J. Lee, B. Lee, S.-H. Kwon, H.-K. Nam, J.B. Choo, K. Yi, Fast Contingency Screening for On-line Transient Stability Monitoring of the KEPCO System, IEEE Power Engineering Society 2001 Summer Meeting, 2001. 7.15-19, Vancouver, Canada.

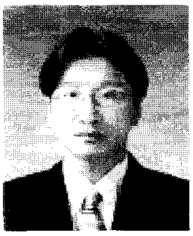
Hae-Kon Nam

He received his B.S degree from Seoul National University, Korea, in 1975, M.S. degree from the University of Houston, Houston, Texas, in 1980, and Ph.D. degree at the University of Texas at Austin, Texas, in 1986, all in electrical engineering. From 1986-1988 he worked as a senior research engineer at the Korea Electrotechnology Research Institute. Since 1988 he has been in Chonnam National University where he is now a Professor of Electrical Engineering. He was also a Visiting Professor at Pennsylvania State University in 1994, and a Visiting Scholar at Powertech Labs Inc. in 2001. His interests include power system stability, and power plant modeling and control.



Yong-Hak Kim

He received his B.S. and M.S. degrees in 1994 and 1996 in electrical engineering at Chonnam National University. He is now with Power Systems Analysis Group, KEPRI. His interests include power system stability and control.



Sung-Geun Song

He received his B.S. and M.S. degrees in 1998 and 2000 in electrical engineering at Chonnam National University. He is now with PROCOM Systems. His interests include power system stability and control.

Yong-Gu Kim

He received his B.S., M.S. and PhD degrees in electrical engineering from Chonnam National University in 1995, 1997 and 2000, respectively. He is now a lecturer in Chonnam National University. His interests include power system stability and control.